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Pink Bollworm Management in Cotton in the Southwestern United States

ABSTRACT

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The pink bollworm (Pectinophora gossypiella (Saunders)) is a major pest in most parts of the world where cotton is grown. Heavy reliance on insecticides for control in the United States has resulted in several peripheral problems. A large number of nonchemical technologies have been researched that have potential as components of an integrated pest management system. None of them alone are completely satisfactory. In this report is discussed the potential of integrating several of these technologies into a single system within the framework of the current knowledge on the biology, ecology, and population dynamics of the insect. The effects of individual technologies on pink bollworm populations are presented in a hypothetical situation to demonstrate the potential of combining several of them into an integrated system of pink bollworm control.

KEYWORDS: Biology, chemical termination, cultural control, environmental factor, insecticides, integrated system, natural enemies, pheromones, pink bollworm, plant growth, varietal resistance, yields.

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CONTENTS

PINK BOLLWORM MANAGEMENT IN COTTON IN THE SOUTHWESTERN UNITED STATES

By T.J. Henneberry[1]

Cotton (Gossypium spp.) is one of the major agricultural crops produced in the United States. Although attempts were made to grow the crop in the 1600's, it was not commercially produced until the late 1700's (Handy 1896). Prior to World War I, the principal cotton producing States were North Carolina, South Carolina, Georgia, Alabama, Mississippi, Arkansas, Louisiana, Tennessee, Oklahoma, and Texas (Lewis and Richmond 1968). Thereafter, cotton became an important crop in Missouri, New Mexico, Arizona, and California. Also, small production areas have been developed in Florida, Nevada, and Virginia.

The estimated value of the crop for the 1981 season exceeded $4.0 billion (U.S. Department of Agriculture 1983b). From 1968 through 1982, harvested cotton areas ranged from 3.6 to 5.6 million ha, yields from 453 to 661 kg of lint per hectare, and total crop values from $1.1 to $4.4 billion.

Ridgway and Lloyd (1983) reviewed the evolution of cotton insect management systems in the United States, noting that reports of losses from cotton insect pests appeared early in the formative years of the cotton industry. The cotton leafworm (Alabama argillacea (Hübner)) and cotton bollworm (Heliothis zea (Boddie)) were reported to cause extensive damage to cotton in the 1800's. However, it is generally agreed that the most important factor affecting the development of cotton insect management systems in the United States was the occurrence of the boll weevil (Anthonomus grandis grandis Boheman) in 1892. Newsom and Brazzel (1968) elaborated on the increasing numbers of cotton insect pest problems that developed in the Southeastern United States concurrent with the general use of insecticides for boll weevil control.

The introduction into the United States of another exotic cotton insect pest, the pink bollworm (Pectinophora gossypiella (Saunders)), ultimately resulted in the development of a parallel complex of insect and related problems in the southwestern cotton growing areas. Recent studies suggest the origin of the pink bollworm in the eastern Indian Ocean area bordered on the east by northwestern Australia and on the west by various islands of the Indonesia-Malaysia area (Common 1958, Wilson 1972). However, the insect was described by W.W. Saunders in 1842 from specimens damaging cotton in India. It apparently reached Egypt in infested cottonseed shipped from India about 1906-7. It was introduced into the Western

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Hemisphere between 1911 and 1913 in cottonseed shipped from Egypt to Brazil, Mexico, the West Indies, and the Philippine Islands (U.S. Department of Agriculture 1977).

The pink bollworm was detected in Texas cotton in 1917 (U.S. Department of Agriculture 1977). The source of infestation was traced to cottonseed shipped in 1916 from Mexico to Texas oil mills. Infestations were apparently eliminated by using cotton-free zones and extensive cleanup measures, as was an infestation discovered in Louisiana in 1919. The insect has persisted along the Mexican border adjacent to west Texas since 1918. In 1936, infestations, probably from windborne moths, occurred again in the lower Rio Grande Valley of Texas and adjacent Mexico, eventually spreading by the mid-1950's to the rest of Texas, New Mexico, Oklahoma, and sections of Arizona, Arkansas, and Louisiana.

In Texas, comprehensive research resulted in the development of effective cultural control methods (mandatory host-free period), and in combination with the discovery of harvest-aid chemicals and mechanical harvesting techniques, the insect has been reduced to noneconomic pest status (Martin and Lewis 1962).

The first pink bollworm infestations in eastern Arizona were reported in 1926. At intervals thereafter, they occurred in other parts of the State and were suppressed through cooperative Federal, State, and industry programs, but infestations spread rapidly after termination of the cooperative efforts in 1963 and were found in the Imperial Valley of California in 1965. Spread was rapid throughout southern California and severe losses occurred by 1967. Infestations were detected in the high desert areas of Los Angeles and San Bernadino Counties in that year, and four moths and six larvae were found in the San Joaquin Valley near Bakersfield. Varying numbers of native moths have been trapped each year except for 1968, and a few larvae were found in the San Joaquin Valley in 1970, 1977, 1980, and 1983. However, by 1985, the San Joaquin Valley remains the only cotton growing area in the Western United States without a firmly established pink bollworm population.

Climatic conditions and economics favor full-season cotton production in the Southwestern United States, and short-season cultural controls, as practiced in Texas, are not accepted or considered feasible. Thus, since 1967, cotton growers in Arizona and southern California have experienced severe economic losses from the pink bollworm due to reduced yields, low quality, and increased costs of insecticides (Watson and Fullerton 1969, Burrows et al. 1982).

A further discussion of the economic impact of the pink bollworm can be obtained by reviewing an economic study on the losses from infestations in the Imperial Valley, CA (Burrows et al. 1982). Losses ranged from 8 to 79 percent of the crop value from 1966 to 1980. The major components of these losses were (1) the cost of chemicals and applications and (2) dollar values associated with yield losses.

Thus, a complex of insect pests attacks cotton in most areas of the Cotton Belt. Management practices to protect the cotton crop from losses are currently required. Schwartz (1983) calculated the potential losses to cotton from some major insect pests using published experimental data for untreated and insecticide-treated conditions (table 1). Losses ranged from 19 to 92 percent in untreated cotton and 0.05 to 30 percent in insecticide-treated cotton. The author cautioned that the data might be biased since the experiments were conducted where high population densities of the species existed. Consequently, the results may not apply to all geographical areas in the country. Also, the insecticides used for control may not have been the best available. Nevertheless, the study showed that insect and mite pests are a major factor in cotton production costs. Other important pests in table 1 may be a problem at sporadic intervals or consistently in certain geographical areas. More detailed information and pertinent literature citations regarding cotton crop losses may be obtained in the reviews by the U.S. Department of Agriculture (1965) and Schwartz and Klassen (1981).

Chemicals are heavily relied on for cotton insect control (Cooke and Parvin 1983). Synthetic organic insecticides are formidable weapons to fight arthropod pests, but serious peripheral problems have emerged. These include the development of insecticide-resistant insect strains, reduction of pest insect natural enemies, resurgence of pest populations in the absence of natural enemies, occurrence of secondary pests, and environmental contamination. Concern over the increasing numbers of these problems has resulted in research to develop alternative methods that do not rely on the unilateral use of insecticides.

Table 1
Calculated cotton losses from some major insect and mite pests of cotton in the United States[1/]

Insects and mites[2/]	Calculated losses: With best control (percent)	Calculated losses: Untreated check (percent)
Boll weevil	20.6	50.7
Heliothis spp.	14.7	63.0
Pink bollworm	9.2	61.0
Cotton fleahopper (*Pseudatomoscelis seriatus* (Reuter))	12.4	34.2
Cabbage looper (*Trichoplusia ni* (Hübner))	29.6	92.5
Aphis spp.	7.9	18.9
Spider mites (*Tetranychus* spp.)	.05	21.3

1/ Calculated by Schwartz (1983) from research reports in Journal of Economic Entomology.

2/ *Lygus* spp., sweetpotato whitefly (*Bemisia tabaci* (Gennadius)), cutworm (*Agrotis* spp.) and others, thrips (*Frankliniella* spp.) and others, and cotton leafperforator (*Bucculatrix thurberiella*) (Busck)) may be sporadic or continuous pests in some areas.

PROGRESS IN DEVELOPING PEST MANAGEMENT TECHNOLOGY FOR COTTON INSECT CONTROL

The definition of integrated control, as developed by a panel of experts of the Food and Agriculture Organization in 1967 and adopted by the Entomological Society of America as embodying the concepts of integrated pest management (Glass et al. 1975), is as follows:

> "A pest management system that in the context of the associated environment and the population dynamics of the pest species utilizes all suitable techniques and methods in as compatible a manner as possible and maintains the pest populations at levels below those causing economic injury."

The integrated pest management approach relies first on natural control factors within the environment of the pest, such as weather, climate, and natural enemies that affect population fluctuations of the pest. Careful monitoring of these and other associated factors identifies the need for supplementary control measures when the pest reaches the threshold level above which the magnitude of loss to the commodity justifies such action on a cost-benefit ratio basis. Ideally, the action taken is pest-specific, is socially acceptable, and does not affect any other facet of the environment.

Improved technology contributed by the research of many scientific disciplines has been brought to bear on entomological problems. Pest suppression methods, such as autocidal techniques, sex pheromones, resistant varieties, and new and improved use of biological agents, are being researched and continually improved and show great potential for use in insect management programs. These advances have made possible consideration of suppressing or eradicating pest insect populations, in some instances in large geographical areas. Management of pest populations focuses on application of control methods that affect the total insect population rather than small local infestations. Knipling (1979) pointed out that moderate and consistent pressure applied each generation to a total insect population is much more effective than intensive suppression applied to a part of the total population.

CONSIDERATIONS FOR DEVELOPING PINK BOLLWORM MANAGEMENT SYSTEMS

Research to obtain essential information for developing management systems for the boll weevil, *Heliothis* spp., *Lygus* spp., and the pink bollworm, as well as other insect and mite pests, is being conducted at a number of locations across the U.S. Cotton Belt by State, Federal, and industry scientists. It is not within the scope of this report to discuss in detail all these pest species. Further comments are restricted to examples of progress being made in the development of technology leading to integrated pest management systems for pink bollworm control, since these examples are typical of research being conducted on other major cotton insect pests.

CROP PRODUCTION, PINK BOLLWORM BIOLOGY, AND ECOLOGICAL RELATIONSHIPS

The first requirement in the development of a pest management system is a thorough understanding of (1) crop production methodology, (2) the biology and ecology of the insect pest, and (3) basic knowledge of its genetics, behavior, and physiology. This information is essential to identify, establish priorities, and integrate control technologies as components of a single effective protection system that is compatible with crop production methodology.

Pest management component technologies concerning the pink bollworm are not all integrated into a single system in any geographical area of the Southwest. However, one or more of the components are practiced in all areas, and with further advancements in refining each method, as well as developing additional methods, potential exists for producing an effective, compatible pest management system.

Crop Development

Cotton grown in most of the Southwestern United States often remains in the ground for 10 to 12 months (Willet et al. 1973). Typically, cotton begins to set bolls during the first fruiting cycle in early June that peaks in early to mid-July. The second fruiting cycle in full-season production systems begins in late July and early August continuing until cool weather, which slows plant growth. The research findings of many scientists have identified pink bollworm suppression methods that can be useful in managing the insect during early-, midseason, and late-season production cycles, as well as after the crop has been harvested (Graham 1980).

Pink Bollworm Biology and Development

The pink bollworm adult is a grayish-brown moth approximately 1 cm long and 0.3 cm wide. Peak moth emergence from pupae occurs from 7 a.m. to 3 p.m. (Lingren 1983). Mating occurs from 2 to 5 a.m. (Lukefahr and Griffin 1957) and generally begins the second night of adult life (Henneberry and Leal 1979). Adults live 2 to 3 weeks and females lay 100 to 200 eggs. Eggs hatch in 3 to 5 days, and larvae develop through four instars in 12 to 18 days, with a pupal stage of 6 to 8 days (Butler and Henneberry 1976). As many as five generations of the insect may occur during the cotton growing season in the Southwestern United States (Slosser and Watson 1972b).

Overwintering and Moth Emergence

Diapause larvae overwinter in cotton bolls, trash, and the soil. During this stage in the life cycle, the insect is subjected to a number of adverse climatic and biological factors that result in mortalities from 48 to 99 percent (Slosser and Watson 1972a, Fullerton et al. 1975, Bariola et al. 1976, Bariola 1983). However, high populations result in survival of sufficient numbers to infest cotton and to reproduce to economic infestation levels (table 2).

Table 2
Spring pink bollworm moth emergence in various cotton growing areas in Arizona and California

Location	Moth emergence[1] per hectare: Year	Average	Range	Variation a result of--	Source
Phoenix, AZ	1967	9,665	2,223-18,525	Cultural practices	Watson and Larsen 1968
		3,853	2,964-5,681	Stalk shredding	Watson et al. 1970
Mesa, AZ	1968	81,922	80,275-83,980	do.	Do.
Meloland, CA	1969	4,817	--	--	Rice and Reynolds 1971
	1970	28,148	--	--	Do.
Mesa, AZ	1968	22,677	9,808-42,272	Plowdown date	Watson et al. 1974
	1969	3,705	395-8,596	do.	Do.
Marana, AZ	1973	63,101	50,400-85,000	Chemical termination	Bariola et al. 1976
Parker, AZ	1974	20,750	13,301-27,400	do.	Do.
Meloland, CA	1975	10,806	4,940-16,673	do.	Bariola et al., unpub. data
Yuma, AZ	1972	15,162	5,901-53,723	Irrigation cut-off	Watson et al. 1978
	1973	12,186	1,853-39,932	do.	Do.
Average	--	23,066	14,338-31,815		

[1]Includes suicidal and reproductive emergence (from Henneberry et al. 1980).

In Arizona and southern California, moths from pupae formed by overwintered pink bollworm larvae begin to emerge in late March and emergence continues into late July and early August (Wene et al. 1961, 1965; Watson and Larsen 1968; Watson et al. 1970; Rice and Reynolds 1971; Slosser and Watson 1972a; Sevacherian et al. 1977; Fye 1979). Eggs laid by these moths produce first generation larvae that enter squares (flower buds) and mature about the time cotton flowering begins. Larvae spin webs that tie the tips of the flower petals together causing the characteristic "rosetted blooms" (Noble and Robertson 1964).

Emergence of overwintering moths before fruiting forms (3 days before cotton squaring, Bariola 1978) of cotton are available as a source of larval food is termed suicidal or nonreproductive (Chapman et al. 1960, Adkisson et al. 1962b).

Hosts

Cotton is the preferred pink bollworm host, but plants of 7 families, 24 genera, and 70 species have been recorded as alternate hosts (Noble 1969). About 43 of these species are found in the Southwestern United States, but they are considered of little importance because of their limited occurrence and lack of attractiveness. Okra is the only other host extensively cultivated in the United States.

Migration

In successful management systems for pink bollworm population suppression, the migratory potential of the insect must be considered. Late-season migrations of pink bollworms of up to 105 km have been well documented (Ohlendorf 1926, McDonald and Loftin 1935, Noble 1969). Pink bollworm moths from overwintered larvae have migrated to cotton isolated 56 km distant from the nearest source of infestation (Bariola et al. 1973b). Also, it appears fairly well documented that pink bollworm moths migrate each growing season from the Imperial Valley of California to the San Joaquin Valley, a distance of over 300 km (Stern and Sevacherian 1978). Moths move within and between cottonfields during the season, and notable peaks of dispersal activity occur in early spring by overwintered moths and again late in the season, when population densities are high and the cotton crop is maturing (Van Steenwyk et al. 1978). Thus, population management efforts must be applied to large areas on an agricultural community basis to be most effective.

Natural Enemies

The role and importance of indigenous parasites and predators in regulating the complex of pest insect populations in cotton, and the need for management systems that minimize the adverse effect of extensive insecticide use that destroys these natural enemies, have been discussed by many authors (Gaines 1942, 1955a, 1955b; Ewing and Ivy 1943; Newsom and Smith 1949; Willie 1951; Van den Bosch et al. 1956; Van Steenwyk et al. 1975).

Quantification of the impact of natural enemies, as a group or as individuals, has been difficult because of the many species involved and the biological interactions within and between beneficial species, as well as with their pest-insect hosts and host plants. Nevertheless, the benefits from preserving natural enemy populations that provide the framework for development of pest management strategies are universally agreed upon.

As to the pink bollworm, the role of predation in population regulation is not well known. Its egg stage is the most vulnerable period in the life cycle since larvae developing within fruiting forms are protected.

Predators commonly found in Arizona and southern California cottonfields that have an essential role in regulating populations of several potential pest species are as follows:

Green and brown lacewings (Chrysopa spp. and Hemerobius spp.), assassin bugs (Sinea spp. and Zelus spp.), damsel bugs (Nabis spp.), bigeyed bugs (Geocoris spp.), minute pirate bugs (Orius spp.), lady beetles, six-spotted thrips (Scolothrips sexmaculatus (Pergande)), striped collops (Collops vittatus (Say)), and syrphid flies (Telford and Hopkins 1957, Wene and Sheets 1962, Van den Bosch and Hagen 1966).

In the field, female pink bollworm moths oviposit principally on vegetative cotton plant parts until mid-July (Brazzel and Martin 1957, Henneberry and Clayton 1982c). During this period, eggs and larvae are exposed to higher risks from predation than later in the season, when oviposition occurs in protected areas of the cotton boll.

Predation of pink bollworm eggs artificially placed in cotton terminals in the field ranged from 95 percent in July to 35 percent in September (Henneberry and Clayton 1982a). The potential of predation has been further demonstrated in the laboratory. Some eggs laid under the calyces of bolls are reached and destroyed by Geocoris punctipes (Say) (Orphanides et al. 1971). Irwin et al. (1974) reported similar results in 48-hour feeding tests with Chrysopa carnea Stephens larvae and adult Geocoris pallens Stål, Orius tristicolor (White), Spanagonicus albofasciatus (Reuter), Nabis americoferus Carayon, and Collops marginellus LeConte.

Several native parasites have also been recognized as attacking the pink bollworm (Nobel 1969). These, as well as several introduced species, have partially controlled the pink bollworm (Jackson 1980). The impact of these natural enemies, as well as opportunities to manipulate populations for maximum benefit and introduce new exotic forms, can only be realized in pest management systems that minimize the general and widespread use of insecticides. Published information strongly suggests that natural enemies have the potential for a major role in early-season population regulation of the species.

Early-Season Environmental Mortality

Early in the season, pink bollworm larvae are subject to extremely high soil temperatures prior to development of the cotton plant canopy that provides shade. Larvae that develop in cotton squares tunnel out of flowers between 9 a.m. and 1 p.m., when soil temperatures can be 60 to 66°C (Butler and Henneberry 1976), and are subject to high mortality (Fye 1971, Clayton and Henneberry 1982), with reduced reproduction of surviving adults (Henneberry and Clayton 1982a).

Pink Bollworm Population Modeling

Thus, biological and environmental factors have an important role in the quantitative population ecology of the pink bollworm. Gutierrez et al. (1977) published a detailed model of

the interaction of the pink bollworm and the cotton plant. The model will be particularly useful for analyzing the population dynamics of the species. Additional biological data are being collected to verify model projections and to improve its performance and application in pest management systems.

Population Development

The reproductive capability of emerging moths from the overwintering generation and the survival of F_1 generation eggs and larvae are adversely affected by several biological and environmental factors. Many moths emerge prior to the availability of host material for reproduction, natural enemies are particularly active in early-season cotton, and extremely high soil temperatures prior to plant canopy cover induce high larval mortality and adversely affect reproduction of surviving adults. Resulting population increase early in the season is low (0.5 to 1.5 X) compared with late-season increases (2.4 to 15.0 X) (table 3, from Graham et al. 1962, Slosser and Watson 1972b, Bariola 1978). Supplementary management strategies designed to exploit this vulnerable time in population development are particularly desirable.

Table 3
Pink bollworm population increases per generation

Generation	Host fruiting form	Data sets (number)	Rate of increase[1/] (number)	Source
F_1	Squares	12	1.3 ± 1.3	Graham et al. 1962, Slosser and Watson 1972b, Bariola 1978
F_2	Squares and bolls	6	15.0 ± 4.3	Do.
F_3	Bolls	9	11.4 ± 9.6	Do.
F_4	do.	3	2.4 ± 3.1	Do.
F_5	do.	1	.8	Bariola 1978

[1/]Averages of available data sets.

Application of strategies to manage the pink bollworm can begin with selection of planting seed and projections of overwintering moth emergence as related to cotton plant development using thermal summation techniques (Sevacherian et al. 1977) to predict the availability of host material.

Host Plant Resistance

The use of genetic characteristics in plants that render them less susceptible to attack from insect pests is one of the most economical and acceptable methods of pest population suppression. Pink bollworm moths require a source of food for maximum oviposition and are known nectar feeders (Lukefahr and Griffin 1956, Lukefahr et al. 1965). Since cotton flowers open during the day, floral nectaries are not readily available during nocturnal activity periods of the insect. Cotton plant types without extrafloral nectaries have been identified and the genetic character has been incorporated into acceptable agronomic types. Seed of a commercial cultivar is currently available and planted by many growers. The value of nectariless cotton for reducing pink bollworm populations in the field was demonstrated by Wilson and Wilson (1976). Pink bollworm infestations have been reduced as much as 50 percent under low population density levels. The resistant nectariless cultivar will not prevent but will reduce population increase in a management system.

Further, Wilson (1982) reviewed the status of breeding for resistance in cotton to pink bollworm and identified 45 cotton stocks that show resistance. No single stock was resistant enough to avoid economic infestation levels. Combinations of the characters are currently being selected and genetic characters incorporated into cotton types with suitable agronomic backgrounds. Nectariless plants, early maturity, and okra leaf seem to be the most promising characters and may be combined in commercial cotton types in the future. Several short-season, early-maturing cotton types, developed throughout the Cotton Belt and grown under southern California conditions, escaped late-season pink bollworm and other insect infestations and produced acceptable yields (Walhood et al. 1983). Further, a recent economic analysis of a pest control alternative in the Imperial Valley, CA, indicates that short-season production systems for the area are economically desirable (Burrows et al. 1982).

Pink Bollworm Population Sampling

Relative magnitude and time of occurrence of pheromone-baited trap catches of early-season pink bollworms indicate moth emergence from overwintering populations that initiate infestations in the current year's crop. Numbers of male moths caught 3 to 4 days prior to the first squaring of cotton are positively correlated to flower infestations during the first fruiting cycle (table 4). The numbers of pink bollworm larvae

in bolls during the first fruiting cycle are positively correlated to flower and boll infestations during the second fruiting cycle. Therefore, careful trap and early-season flower infestation monitoring can provide useful information for estimating the extent and magnitude of the moth population that will subsequently oviposit and produce larvae in bolls that cause economic losses.

Additional research to provide more data and further refine this technique is needed to quantitatively estimate the extent of boll infestations as related to early-season moth catches and flower infestations. A decision-making tool is urgently required to determine the need for control action early in the season based on estimates of population density.

Table 4
Correlation coefficients1/ of relationships between male pink bollworm (PBW) moth trap catches 3 to 4 days prior to cotton squaring (flower buds) and subsequent flower and boll infestations2/

	Dependent variables			
	Rosetted blooms (%)		PBW life stages per 100 bolls	
Independent variables	(1)3/	(2)4/	(1)3/	(2)4/
Moths/trap/night, May 15-18 avg.	0.845***	0.267	0.278	0.089
Moths/trap/night, May 15-18 max.	.809***	.268	.322	.186
Rosetted blooms, %	--	.471	--	.214
PBW life stages/100 bolls	--	.621**	--	.627*

1/Critical r; N = 17; 0.482, 5%*; 0.606, 1%**; 0.725, 0.1%***. (Asterisks = critical probability levels.)

2/From Beasley et al. 1985.

3/(1) Prior to end of 1st flower cycle.

4/(2) After end of 1st flower cycle.

Planting Date and Suicidal Emergence in Pink Bollworm Population Management

Percentages for a typical pattern of pink bollworm moth emergence from pupae formed by overwintering diapause larvae are shown in figure 1.

Approximately 95 percent of moths emerge from mid-March through mid-June. Cotton fruiting forms (squares) are present in Arizona and southern California cotton between mid-May and early June for cotton planted between March 20 and April 20. Under these conditions, suicidal emergence can range from 57 to 86 percent in the desert valley growing areas of Arizona and California (Wene et al. 1965, Watson and Larsen 1968, Watson et al. 1970, Rice and Reynolds 1971, Slosser and Watson 1972a, Bariola 1978).

Published data suggest the possibility of delaying the planting date to prolong the period of suicidal emergence (Adkisson et al. 1962b). Table 5 shows the effect of cotton planting dates on early-season pink bollworm flower and boll infestations. This cultural practice may be a useful management tool in areas where good plant stands can be established later in the season and effective additional methods are employed to protect late-season bolls. Also, the planting dates must be accepted by all growers in a management area.

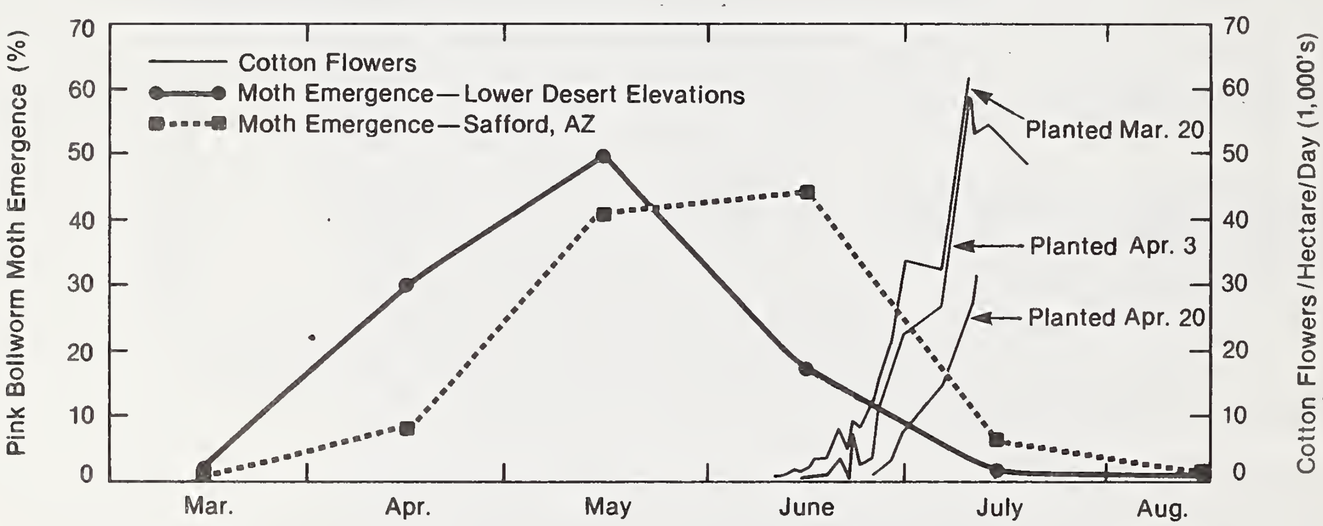

Figure 1
Typical pattern of emergence of pink bollworm moths in Arizona and southern California (from Henneberry et al. 1980).

Table 5
Average percentages of pink bollworm-infested cotton flowers and bolls in plots planted Apr. 9 and May 7[1]

Sampling date		Flowers[2] on cotton planted--				Bolls infested on--	
		Apr. 9		May 7		Apr. 9	May 7
		(number)	(percent infested)	(number)	(percent infested)	(percent)	(percent)
June	15	<1	0	--	--	--	--
	18	5	7	--	--	--	--
	22	22	5	--	--	--	--
	25	20	2	--	--	--	--
	27	36	2	--	--	--	--
	29	54	4	--	--	--	--
July	2	66	4	--	--	--	--
	6	51	2	8	0	--	--
	9	39	2	6	0	--	--
	11	41	1	13	0	--	--
	13	56	1	21	0	--	--
	16	148	2	54	1	--	--
	18	154	3	67	1	--	--
	23	127	3	51	<1	16	3
	25	113	5	58	3	--	--
	27	115	5	75	3	34	16
	30	138	5	128	3	--	--
August	6	98	1	109	2	45	18
	13	71	<1	91	1	38	19

1/From Henneberry et al. 1982.

2/First flowers on cotton planted May 7 averaged 18 days later than first flowers on cotton planted Apr. 9.

Behavioral Control With Gossyplure

The role of insect pheromones in mediating behavior of insects to disrupt mating and prevent insect reproduction was first suggested by Beroza (1960).

The pink bollworm sex pheromone was identified in 1973 as a 1:1 ratio of _Z_,_Z_- and _Z_,_E_-isomers of 7,11-hexadecadienyl acetate and named "gossyplure" (Hummel et al. 1973). Since then, extensive studies have been conducted to determine the potential of the pheromone as an integrated pest management tool in cotton production systems.

Gossyplure is permeated in the atmosphere of cottonfields at rates to disrupt moth communication, inhibit male moth orientation, prevent or reduce mating, and provide so many pheromone point sources that male moths are "confused" or involved in "false trail following," which also results in reduced mating.

Promising research results, indicating the potential of gossyplure for behavioral control by mating disruption (Shorey et al. 1976, Gaston et al. 1977), resulted in the development of controlled-release gossyplure carrier systems for use in commercial cottonfields.

At present, two slow-release systems for gossyplure are commercially available: (1) NoMate PBW (Albany International Company, Needham, MA; gossyplure contained in 1.5-cm long, polyacetal resin hollow fibers), and (2) Disrupt (Hercon Division, Health Chem Corporation, New York, NY; gossyplure contained in middle layer of 0.3 cm^2, 3-layer plastic laminate system). NoMate PBW fibers, suspended in Bio-Tac and Disrupt flakes suspended in Phero-Tac, are aerially applied using special equipment designed by the respective manufacturers (Funkhauser 1979, Kydonieus et al. 1982). Commercial applications of NoMate PBW (Brooks and Kitterman 1977, Brooks et al. 1979, Doane and Brooks 1981) and Disrupt (Butler et al. 1983) have appeared promising for pink bollworm control as compared with scheduled insecticide applications for early-season pink bollworm control. Also, under low population density and controlled experimental conditions, gossyplure reduced seasonal average boll infestations 68 percent and female mating 50 percent (Henneberry et al. 1981).

The practice of including small amounts of pyrethroid insecticide (about 4.5 g.a.i./ha) to the adhesive sticker used with the hollow-fiber system was suggested by Staten and Haworth (1981) and has, with various modifications, become common in commercial usage during the last few cotton growing seasons.

Most pheromone treatments have been terminated by mid-August and replaced with insecticide applications when high pink bollworm population densities occur.

Table 6 shows published results of some research conducted to evaluate commercial applications of gossyplure for early-season pink bollworm control. Although additional research is needed to improve use patterns of commercial formulations, develop improved formulations, and determine the quantitative effect of gossyplure on pink bollworm population dynamics, the use of gossyplure has potential as a component of pest management systems for early-season control under low population densities.

Table 6
Percentages of pink bollworm-damaged, mature cotton bolls in gossyplure- and insecticide-treated fields at various locations in California and Arizona from late July to mid-September[1]

Treatment	IVCa [2]		PV,AZ[2]		PVCa[2]
	7/27-8/10 1981	8/11-27 1981	8/6-7 1980	8/3-18 1981	8/24-9/16 1982
NoMate PBW:					
Alone	5	13	--	--	1
Plus other insecticides	3	--	--	--	--
NoMate PBW, pyrethroid:					
Alone	<1	1	2	1	1
Plus other insecticides	1	3	--	--	--
Disrupt:					
Alone	--	--	--	0	11
Plus pyrethroid	--	--	--	--	5
Scheduled insecticides	1	3	5	--	2

[1]From Beasley and Henneberry 1983 and Butler et al. 1983.

[2]IVCa = Imperial Valley, CA; PV,AZ = Parker Valley, AZ; PVCa = Palo Verde Valley, CA.

Additionally, the mechanisms involved in mating disruption with gossyplure have been postulated to involve sensory adaptation, central nervous system habituation, and confusion (Shorey 1976). Flint and Merkle (1983) found that communication disruption, resulting in reduced pink bollworm male moth catches in baited traps and mating of moths on mating tables, occurs in fields treated with only one of the two component isomers of gossyplure. Further, males respond more to traps baited with 9:1 ratios of the two gossyplure isomers than to traps baited with 1:1 ratios normally used and previously reported as the ratios existing in females (Hummel et al. 1973). The mechanism causing the behavioral alteration is thought to be the male moth perception of abnormal pheromone imbalance creating an environment that is not suitable to finding a mate. The potential use of individual gossyplure components to achieve pheromone imbalance needs further investigation as a new application of behavioral modification for insect control.

Chemical Control

A number of effective insecticides are available for pink bollworm control. They remain a vital component of management systems, but should not be used indiscriminately on a scheduled basis. They should be used as a supplement to cultural or other control measures.

The pink bollworm is a late-season pest and damaging infestations rarely occur before late July to early August. At that time, chemical control may be necessary to prevent serious economic losses; however, sizable initial pink bollworm infestations can be tolerated without reduced cotton yields (Watson and Fullerton 1969). Insecticide applications should be made on a field-by-field basis after careful monitoring of the crop environment and indirect estimating of the population using sex pheromone traps.

Pink Bollworm Population Sampling

The number of insecticide applications can be reduced markedly if treatment is based on boll infestation data or pink bollworm moth density as measured by trapping rather than applications made on routine schedules (Toscano and Sevacherian 1980).

Adkisson et al. (1962a) and Watson and Fullerton (1969) showed that at least 20 percent of the firm green bolls could be infested before control measures were warranted. However, common practice is to undertake treatments when 5 to 10 percent of the bolls are infested. Fry and Henneberry (1983) developed an experimental model to demonstrate that the maximum number of pink bollworm susceptible bolls mostly occur about 3 weeks after peak flowering. Thus, maximum protection must be afforded during this period. The model indicates that after peak flowering fewer bolls are available and higher pink bollworm levels may occur but have less effect on total yield. With additional refinement, the model can be a useful tool in estimating potential lint loss on a weekly basis to determine whether or not the additional cost for pink bollworm control is justified.

Reynolds (1980) reviewed the current state of the art regarding the use of insecticides for pink bollworm control. He observed that insecticides are our main defense but should be used as a last resort or as a supplement to cultural or other control measures. Timing of applications is particularly critical, since control effectiveness is based on killing adult moths. When susceptible bolls are available, eggs are laid under the calyx or on bracts and are relatively inaccessible to insecticide deposits. Larvae enter the boll soon after hatching from eggs and are not killed by insecticides when they are within the boll. Decisions to apply insecticides should be based on field monitoring to determine pink bollworm populations and the stage of plant growth (Reynolds 1980, Fry and Henneberry 1983).

When susceptible cotton bolls are first available in large numbers (June through July), catches of 12 to 15 male moths per pheromone trap per night indicate the need to initiate control action (Toscano et al. 1979). The relationship between trap catches and boll infestations are shown in figure 2. Trap catch data thereafter are more difficult to interpret, since numbers of moths caught are not reduced or reduced for only 1 to 2 days following insecticide application, even though insecticides are effectively reducing boll infestations (Henneberry and Clayton 1982b). This is difficult to explain but may be related to continuing emergence in fields or between field movement of moths. In any event, management of pink bollworm populations with chemicals during peak availability of susceptible cotton bolls must be accomplished using boll sampling methods to

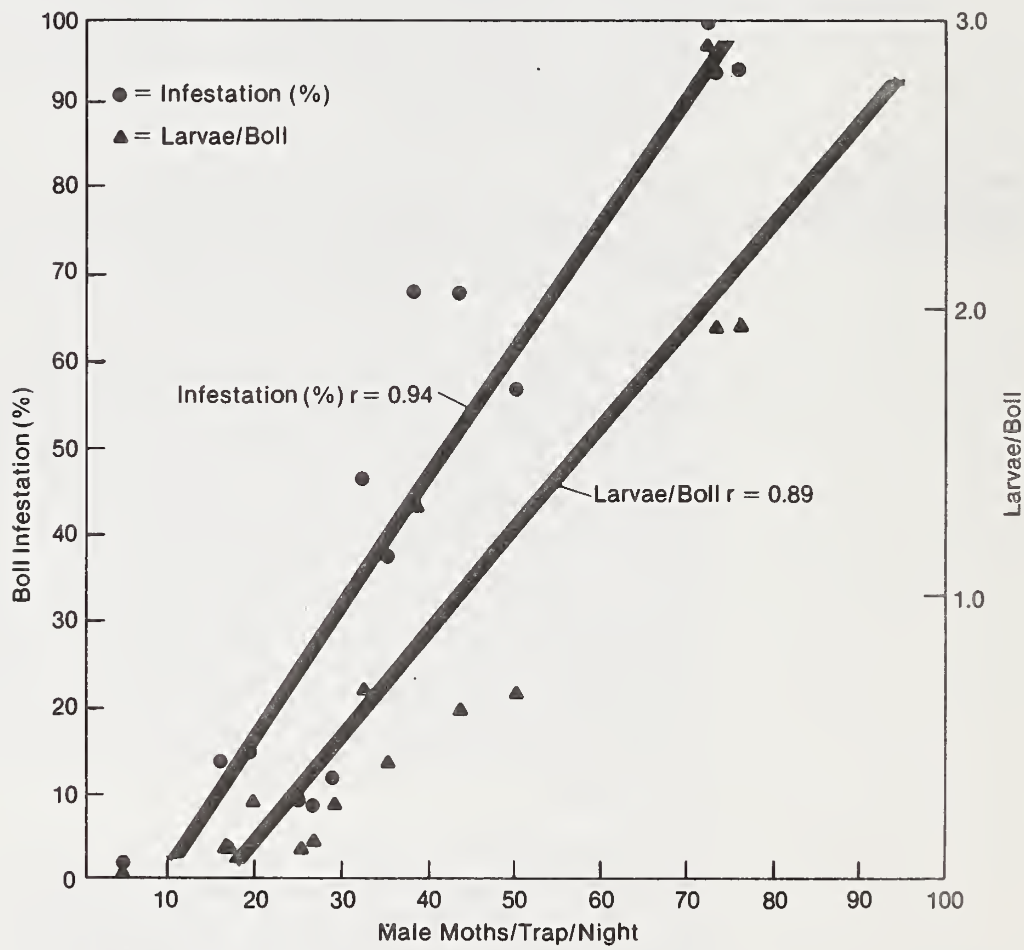

Figure 2
Relationships between numbers of pink bollworm male moths caught per trap per night, boll infestations, and larvae per boll.

estimate infestation levels on a field basis, as previously described (Toscano et al. 1979).

Specific recommendations as to choice of insecticides, rates of application, and use patterns vary according to areas. These are continually updated. The most efficient pest management specialists will keep current with the most recent technology available through agricultural experiment stations and Federal and State extension agencies.

Development of insecticide resistance is one of the most difficult problems facing the cotton industry. The pink bollworm developed resistance to DDT (1,1,1-trichloro-2,2-bis) in Mexico and Texas in the 1950's and '60's (Lowry and Berger 1965). There are no documented cases of pink bollworm resistance to organophosphorous compounds (Reynolds 1980). However, Bariola (1985) indicated that tolerance to certain synthetic pyrethroid compounds has occurred. This is of particular concern since documented entomological experiences over the years show that once resistance occurs in a population, it develops more rapidly to other types of insecticides. The only feasible method to prolong the life of insecticides currently available is to reduce the selection pressure that results in the development of resistant strains. Therefore, integrated pest management systems in which insecticides must be used need to incorporate cultural and other available control technologies to reduce pest target populations and insecticide use in order to minimize effects on nontarget organisms and avoid other adverse peripheral effects previously discussed.

Diapause larvae may occur as early as late August, but the incidence is low until mid-September, rising to 50 percent or more by October 1 and 80 percent by mid-October (fig. 3). Insecticide applications are generally terminated in mid- to late September because of high treatment costs and reduced benefits of potential yield increases. Thus, high populations of the insect occur in bolls that are the diapause overwintering generation.

Typically, 85 percent of the total number of cotton bolls produced are set by September 15. Bolls set after late August to mid-September may not mature or may produce fiber of low quality (Bennett et al. 1967). Under southwestern growing conditions, bolls may be produced until frost. Thus, high percentages of the diapausing pink bollworm larvae develop in bolls that may not contribute significantly to yield, but do provide a source of pink bollworm infestation for cotton planted the following year. In most instances, over 99 percent of the diapausing larval generation develops in bolls after September 15 (fig. 3). Crop management systems that minimize yield losses while reducing overwintering pink bollworm populations by limiting the availability of host material after mid-September or that induce high mortality of diapause larvae are essential components of pest management in southwestern full-season production systems. Various methods have been proposed to accomplish these objectives.

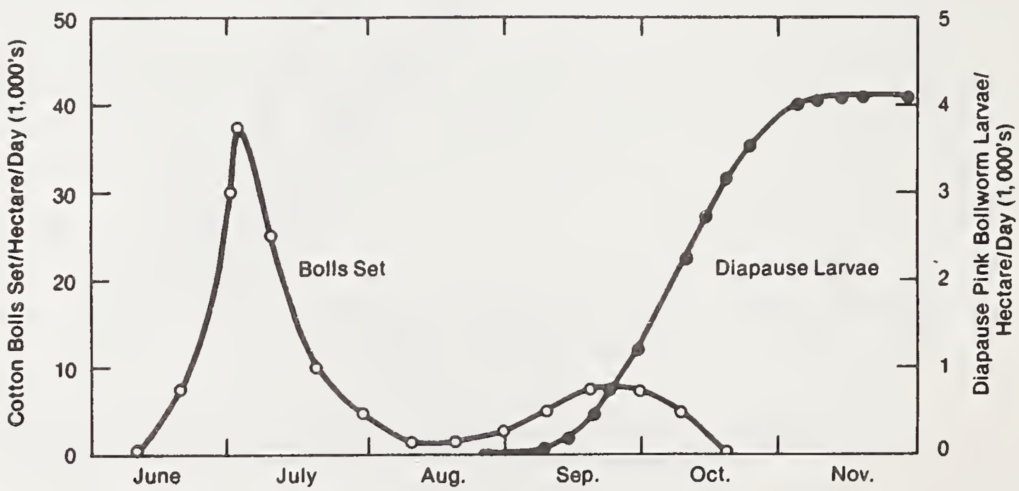

Figure 3
Typical seasonal boll production curve and occurrence of diapause pink bollworm larvae in Arizona and California cottonfields (from Kimball et al. 1977).

Selective Removal of Host Material

This concept was demonstrated by manually stripping all fruiting forms from cotton plants on October 1, 15, and November 1 (Chapman and Cavitt 1937). The diapause larvae in the soil were reduced by 75, 51, and 18 percent, respectively, as compared with those found when fruiting forms were stripped from plants on November 15.

Similar results were obtained with early chemical applications of cotton defoliants or desiccants in Texas, California, and Arizona (Adkisson 1962, Rice et al. 1971, Kittock et al. 1978). However, early defoliation or desiccation treatments remove cotton leaves and, in fact, terminate further cotton production, often resulting in reduced cotton yields (Walhood 1960, Kittock et al. 1973) and quality (Kittock et al. 1978).

Selective removal of cotton fruiting forms during mid-September with plant growth regulators appears to have the most potential in limiting late-season pink bollworm host material (Mauney et al. 1972). Numbers of diapausing pink bollworm larvae decrease in relation to the reduction of immature bolls. The treatments have the least adverse effect on cotton yield and quality because leaves remain on the plant and existing green bolls continue to develop normally.

Treatments have been developed that selectively remove late-season cotton fruiting forms and reduce pink bollworm fall populations at harvest by more than 90 percent (Bariola et al. 1976). None of the treatments at present are completely acceptable because of adverse effects on the plants that contribute to reduced yield or harvesting. However, the concept is valid, and the development of an acceptable treatment is highly probable. Studies are currently being conducted with two plant growth regulators that are registered on cotton for other use (Henneberry and Bariola 1985). Preliminary results appear promising.

Early cotton crop termination by water management techniques to shorten the growing season, to reduce the amount of late-season host material, and to prevent development of large overwintering pink bollworm populations is another approach, with high potential for success in certain cotton growing areas. In the Yuma Valley, AZ, plants receiving the last irrigation on July 29 slightly outyielded plants receiving the last irrigation on August 16 and September 3 (Watson et al. 1978). Greater numbers of pink bollworm moths emerged the following spring with each subsequent irrigation cutoff date. Thus, the last irrigation about August 1 in the Yuma Valley would maintain crop yield and minimize the number of overwintering pink bollworm larvae.

Destruction of Diapause Larvae

Destruction of pink bollworm diapause larvae in their overwintering habitat by combined mechanical and cultural means is one of the most effective management tools for pink bollworm population suppression (Watson 1980).

Stalk shredding to enhance uniform and deep burial of shredded plant debris, followed by disking and effective plowing and winter irrigation treatments, effectively reduces the numbers of overwintering pink bollworms (Watson 1980). The most effective, practical tillage practice has been deep plowing that results in turning over the soil to a depth of 15 cm. The earlier winter plowing is accomplished, the higher the larval mortality, with fewer moths emerging in the spring. Tillage practices, such as disking and winter irrigation, also induce additional winter mortality (Watson 1980).

MANAGEMENT TO PREVENT ESTABLISHMENT IN UNINFESTED AREAS

Sterile Insect Release Barrier Zones

The sterile insect release method remains a highly viable pink bollworm population suppression tool. Newly emerged pink bollworm moths exposed to 25 krad of gamma radiation or more and crossed with untreated insects produced no fertile adult progeny (Graham et al. 1972). Sterile moth releases (15-40 krad) in field cages with untreated insects reduced developing pink bollworm populations 72 to 91 percent over two generations (Richmond and Graham 1970, 1971). Results of similar field cage studies (Bariola et al. 1973a, Flint et al. 1974, 1975) also indicated that the method showed promise as a control technique.

Development of a pink bollworm artificial diet (Vanderzant and Reiser 1956) and mass rearing technology (Richmond and Ignoffo 1964) have led to a specialized use of the pink bollworm sterile release method in the uninfested San Joaquin Valley of California, where more than 400,000 ha of cotton are grown annually. Releases have been made by air in areas ranging from 6,000 to 145,000 ha of cotton, where native moths were trapped or larvae found in bolls. The purpose of the releases is to provide a barrier zone of sterile insects to prevent reproduction of migrating native moths from infested areas.

Releases of sterile pink bollworm moths have been made during the cotton growing seasons in the noninfested area each year since 1968 (table 7). Native male moths have been trapped in the valley each year of the program and larvae found in bolls in each of 5 years. Further, overwintering pink bollworm larvae have survived and emerged in the spring in the Bakersfield area of the San Joaquin Valley (Bartlett and Staten, unpub. data). Thus, based on indirect evidence that the insect has not become established, it appears the releases of sterile moths that maintain average sterile-to-native ratios of more than 200:1 (Knipling 1978) throughout the season have prevented the establishment of the insect.

Potential of Sterile Pink Bollworm Moth Releases in Infested Areas

Several field studies with releases of sterile pink bollworm moths to evaluate this method for suppressing established populations were unsuccessful (Bariola et al. 1973a, Graham 1978). This was attributed to the effect of lack of isolation from migrating native pink bollworm populations into the experimental areas and high native populations. Consequently, it was difficult to obtain ratios of sterile-to-native insects sufficient to achieve population suppression.

One of the essential elements for the successful application of the sterile insect release method for established infestations is that initial releases must produce high enough ratios of sterile-to-native insects to start a downward trend in the population. Thus, populations of most pest species must be reduced considerably by other means before a sterile insect

Table 7
Numbers of sterile pink bollworm moths released, sterile and native male moths trapped, and larvae found in San Joaquin Valley, CA, 1967 to 1983[1]

Year	Traps (number)	Sterile released moths (millions)	Male moths caught[2] Sterile (number)	Native (number)	Larvae[3] found (number)
1967	850	--	--	4	6
1968	2,100	9	20	0	0
1969	5,850	8	564	5	0
1970	4,000	100	26,428	13	3
1971	8,600	108	11,159	12	0
1972	46,000	100	59,080	36	0
1973	49,311	90	37,656	25	0
1974	32,280	37	28,289	[4]940	0
1975	22,047	150	1,528,260	245	0
1976	27,449	194	1,229,742	1,474	0
1977	33,711	412	1,677,900	7,402	4
1978	19,606	456	429,063	69	0
1979	20,591	637	545,295	754	0
1980	20,809	511	566,170	4,492	9
1981	19,390	794	864,861	[4]3,727	0
1982	16,933	772	1,041,280	[4]128	0
1983	12,850	594	1,057,735	[4]931	4

[1] From U.S. Department of Agriculture 1977, 1983a.

[2] 1967 to 1973, hexalure-baited traps; 1974 to present, gossyplure-baited traps.

[3] Samples of cotton fruiting forms ceased when immature pink bollworms were found.

[4] 1974 includes 503; 1981, 3,050 (also 2 larvae); 1982, 4; and 1983, 68 moths from Cantil area adjacent to San Joaquin Valley.

release program will be feasible. The optimum time to begin such a program is when the native population is at its lowest level. At the present time, discussion of the potential use of the method for pink bollworm management in the Southwestern United States is academic since indigenous populations are too high to consider the techniques as economically or physically feasible.

Pink bollworm moths, which were from larvae mass-reared on an artificial diet containing a red dye to distinguish released sterile insects, were sterilized by exposure to 20 krad of gamma radiation in a Co^{60} irradiator at the pink bollworm rearing facility of the Animal and Plant Health Inspection Service, Phoenix, AZ. Air shipments of 50,000 to 100,000 sterile moths were initiated 4 days weekly on December 28, 1980, from Phoenix to St. Croix, U.S. Virgin Islands, and continued through March 31, 1982. Releases of sterile pink bollworm moths were made on 216 days from December 29, 1980 to April 1, 1982, and averaged about 100,000 per release day (Henneberry and Keaveny 1985).

Prior (Jan. 1 to Dec. 28, 1980) to the initiation of the large-scale releases of sterile pink bollworm moths in cotton plots, larval infestations in bolls averaged about one larva per boll from January through July 1980, increased to over seven in August, and decreased to 1.5 in December 1980 (fig. 4). Ratios of released sterile male to St. Croix male moths in gossyplure-baited traps averaged about 1:1 during January to April 1981, and releases had no effect on larval infestations. Reductions of larval infestations in bolls began when ratios of released sterile male to St. Croix male moths averaged about 70:1. Numbers of larvae per boll decreased from 1.2 in May to 0.3 in August. Infestations increased and ranged from 1 to 2.9 larvae per boll during September 1981 to March 1982, when ratios of released sterile male to St. Croix male moths in gossyplure-baited traps averaged 20:1. When releases of sterile moths were terminated on April 1, 1982, the pink bollworm larvae per boll increased from 1 to 3.7 over a 58-day period during April to late May 1982.

Released sterile moths were found to be noncompetitive with native males in obtaining native female partners using several sampling techniques. However, when ratios of released sterile moths to native insects were high enough, larval infestations in bolls were reduced.

Assuming other management technologies were effectively integrated into a systematic effort to suppress pink bollworm populations and the quality of released sterile insects can be improved, the sterile-release system may be considered a viable component of a total management system in the future.

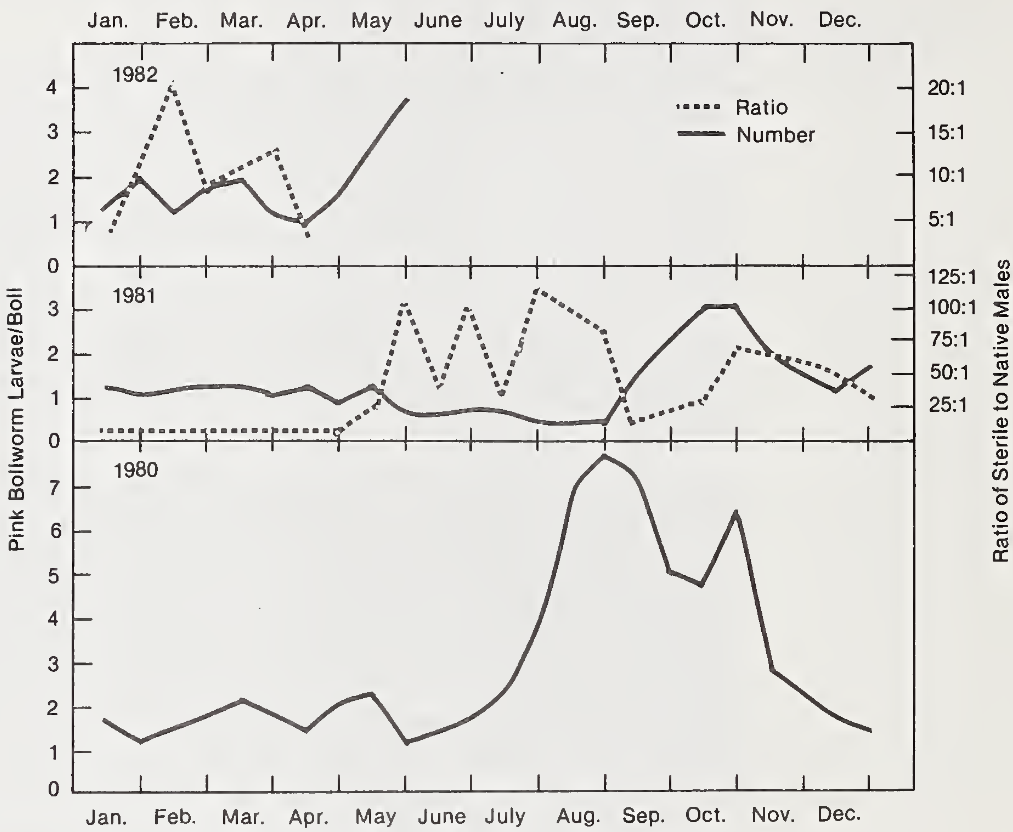

Figure 4
Average number of pink bollworm larvae per cotton boll in cultivated cotton on the Kingshill and Virgin Islands Experiment Stations in 1980 before (Jan. 1, 1981, to Mar. 31, 1982), during (Apr. and May 1982), and after releases of sterile moths, with ratios of sterile to St. Croix native males caught in gossyplure-baited traps.

POTENTIAL OF INTEGRATING PINK BOLLWORM MANAGEMENT TECHNOLOGIES INTO A SINGLE POPULATION SUPPRESSION SYSTEM

The various pink bollworm management strategies discussed are listed in table 8, with the estimated impact on pink bollworm populations calculated from published field research results by several scientists. The data are not meant to be exhaustive or a complete summary. They illustrate the potential use of the known available control technology in an integrated approach to management of pink bollworm populations in the arid cotton-growing areas of the Southwestern United States.

Table 8
Pink bollworm management strategies, potential of integration into systems approach, and calculated impact on pink bollworm numbers based on published research reports

Management strategies	Data sets (number)	Estimated reduction in pink bollworms by generations-- 1 and 2 (percent)	3 and 4 (percent)	5 (percent)	Source
Early season:					
Plant resistance	12	37.9 ± 12.5	0	0	Wilson and Wilson 1976, Wilson et al. 1980, Wilson et al. 1981
Planting date	2	54.0 ± 25.5	0	0	Henneberry et al. 1982
Behavioral control (gossyplure)	1	68.0	0	0	Henneberry et al. 1981
Predation	8	67.9 ± 19.1	(?)	(?)	Henneberry and Clayton 1982c
Environmental mortality	16	57.1 ± 27.1	(?)	(?)	Henneberry and Clayton 1979, Clayton and Henneberry 1982
Midseason to late-season chemical control	23	--	80.3 ± 19.9	--	Watson and Fullerton 1969, Henneberry et al., 1977, 1978, Vail et al. 1978, George and Wilson 1983, Bariola et al. 1984
Late-season:					
Chemical termination	14	--	--	71.2 ± 27.3	Bariola et al. 1976, Kittock et al. 1978, Bariola et al. 1981
Irrigation cutoff	13	--	--	50.2 ± 27.5	Watson et al. 1978, Bariola et al. 1981, Walhood et al. 1981
Postseason:					
Tillage	3	--	--	55.7 ± 33.3	Watson and Larsen 1968, Watson et al. 1974
Natural winter mortality[1]	23	--	--	82.8 ± 15.3	Slosser and Watson 1972a, Fullerton et al. 1975, Bariola et al. 1976, Bariola 1983
Other	--	--	--	(?)	--

[1]Soil moisture, texture, composition, predators, etc.

Percentages in the table were calculated as the average seasonal reduction in numbers of pink bollworms or seed damage in appropriately treated cotton versus those in untreated controls in the case of plant resistance, planting date, and behavioral and chemical control. Percent reductions as a result of chemical termination, irrigation cutoff, and tillage practices reflect differences in reproductive moth emergence in the spring in treated fields versus emergence in control plots. Calculated reduction percentages for spring and winter environmental mortality were based on emergence from pupae formed by known numbers of diapause larvae under the appropriate experimental conditions.

Reduction in average seasonal numbers of pink bollworm or adult emergence as a result of spring or winter mortality factors ranged from 37.9 to 82.8 percent. Theoretically, emerging moth populations of more than 60,000 per hectare from pupae formed by overwintering larvae, if subjected to all the technologies listed, would be reduced to emergence of a few moths per hectare the following year. This projection is probably optimistic in that the data summarized in table 8 were collected in independent studies. Management technologies discussed are not mutually exclusive, but they interact within the system. No allowance for the interactions is possible within the present analysis. Further, pink bollworm moths are highly mobile, and movement into and out of a management system would have to be considered. The data do, however, illustrate the potential of integrating a number of population suppression technologies into a single system for managing the insect within the crop production year. Research is urgently needed that incorporates a number of the discussed technologies into a system approach to areawide pink bollworm management.

SUMMARY

Pink bollworm population development is affected by a large number of biotic and abiotic factors. The overwintering generation and subsequent spring emergence insects are subject to high mortality factors that result in a low (0.5 to 1.5 X) population increase during the first generation that infests the current year's cotton crop. Consequently, supplementary early-season suppression technology, such as resistant plant types, planting dates to increase suicidal emergence, and behavioral control with pheromone techniques, has the potential to greatly further reduce population increase.

Midseason to late-season control is heavily reliant on chemicals. Careful sampling with sex pheromone-baited traps and examination of bolls to determine application of insecticides on a "need" basis can notably reduce numbers of applications and cost of chemical control.

Late-season management systems to reduce development of the diapause pink bollworm generation by eliminating host material or destroying diapause larvae, using tillage or irrigation techniques, are the most powerful and economical methods of population suppression of the insect.

A theoretical analysis of the impact of integrating existing technology into a single management system indicates that application of the system to a large area would reduce the pink bollworm population to subeconomic levels in 1 year.

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